A STUDY OF METHODS TO PREDICT AND MEASURE THE
TRANSMISSION OF SOUND THROUGH THE WALLS OF LIGHT AIRCRAFT

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Submitted by:

        R.J. Bernhard, Principal Investigator
        J.S. Bolton, Assistant Professor
        B. Gardner, Research Assistant
        J. Mickol, Research Assistant
        C. Mollo, Research Assistant
        C. Bruer, Research Assistant

Approved by:

        Raymond Cohen, Director
        Ray W. Herrick Laboratories

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This is a semi-annual status report for NASA Grant NAG1-58 for the period May 15, 1986 through November 15, 1986.

RESEARCH PROGRESS

Research investigations either fully or partially supported by NASA for the semi-annual reporting period progressed toward the following objectives:

1. Development of a numerical/empirical noise source identification procedure using boundary element techniques.

2. Identification of structure-borne noise paths using structural intensity and finite element methods.

3. Development of a design optimization numerical procedure to be used to study active noise control in three-dimensional geometries.

4. Measurement of dynamic properties of acoustical foams and incorporation of these properties in models governing three-dimensional wave propagation in foams.

NUMERICAL/EMPIRICAL NOISE SOURCE IDENTIFICATION PROCEDURE   (Bryce Gardner)

The experimental verification of the direct boundary element techniques (DBEM) is continuing. First, a tube to measure the acoustic impedance of materials was built to comply with the standard test method (ASTM E1050-85a). An extension for the tube was built to extend the useful frequency range of the device down

to about 100 Hz. This tube will be used to make standard impedance measurements as well as being adapted to make in situ impedance measurements. These impedance values will then be used as boundary conditions for the DBEM program. The impedance tube, may also be used as a calibrated source. If used with an open end, the volume velocity at the end can be calculated by a two microphone technique similar to the impedance calculation. Software has been developed to calculate the volume velocity, impedance and other acoustical properties.

The majority of the analytical work in this reporting period has centered around the box cavity. The box cavity has several intrinsic differences from the sphere cavity which make it interesting to study. First, the box cavity can be precisely modeled by flat triangular elements. The sphere model exhibited a frequency shift in the results which was attributed to the deviation of the model (which was made of flat triangles) from a perfect sphere. As expected, the results in the box cavity showed a much smaller frequency shift which was noticeable mainly at higher frequencies.

Secondly, the box cavity has sharp corners and edges. The integrations near a corner or edge are not done well due to the influence of the near singularities of Green's function and it's derivatives in these situations. One modeling technique that improves the results is to keep the centers of the elements as far from the corner as possible, (Fig. 1-1). In the 156 element box model, this change to one half of the corner elements made a
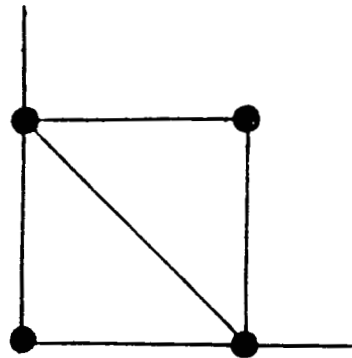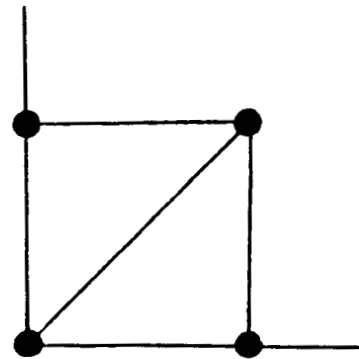
Poor Model   Good Model

Figure 1-1. Alternative models near edges and corners.

significant difference in the results (Fig. 1-2). Another way to improve the results is to improve the integration techniques. Two ways to do this are being studied. The first is to use a better integration quadrature. Some higher-order gauss quadratures have been inserted into the program. These higher order quadratures give better results especially for the larger models. A rule to choose the optimum quadrature for each integration needs to be derived and implemented. The second technique to improve the integration techniques is to improve the behavior of the functions to be integrated. A way of separating the part of the functions that tend to be singular from the rest of the function is under investigation. In this technique the well-behaved portion would be integrated as usual but the portion that is ill-behaved would be integrated either analytically or with a combination of analytical and numerical procedures.

The third reason for considering the box cavity was it's applicability to the experimental verification. The box model was designed with the same dimensions as the plywood box cavity in the lab. This box, with sand-filled plywood walls is close to a perfectly rigid cavity. The most straight forward verification of the DBEM program requires putting the impedance tube into the box as a calibrated source and measuring the pressure at various locations in the box. Some data has been taken but has not yet been reduced.

Recently, Bruel and Kjaer brought a new product, the Spatial Transformation of Sound Fields (STSF) hardware and software
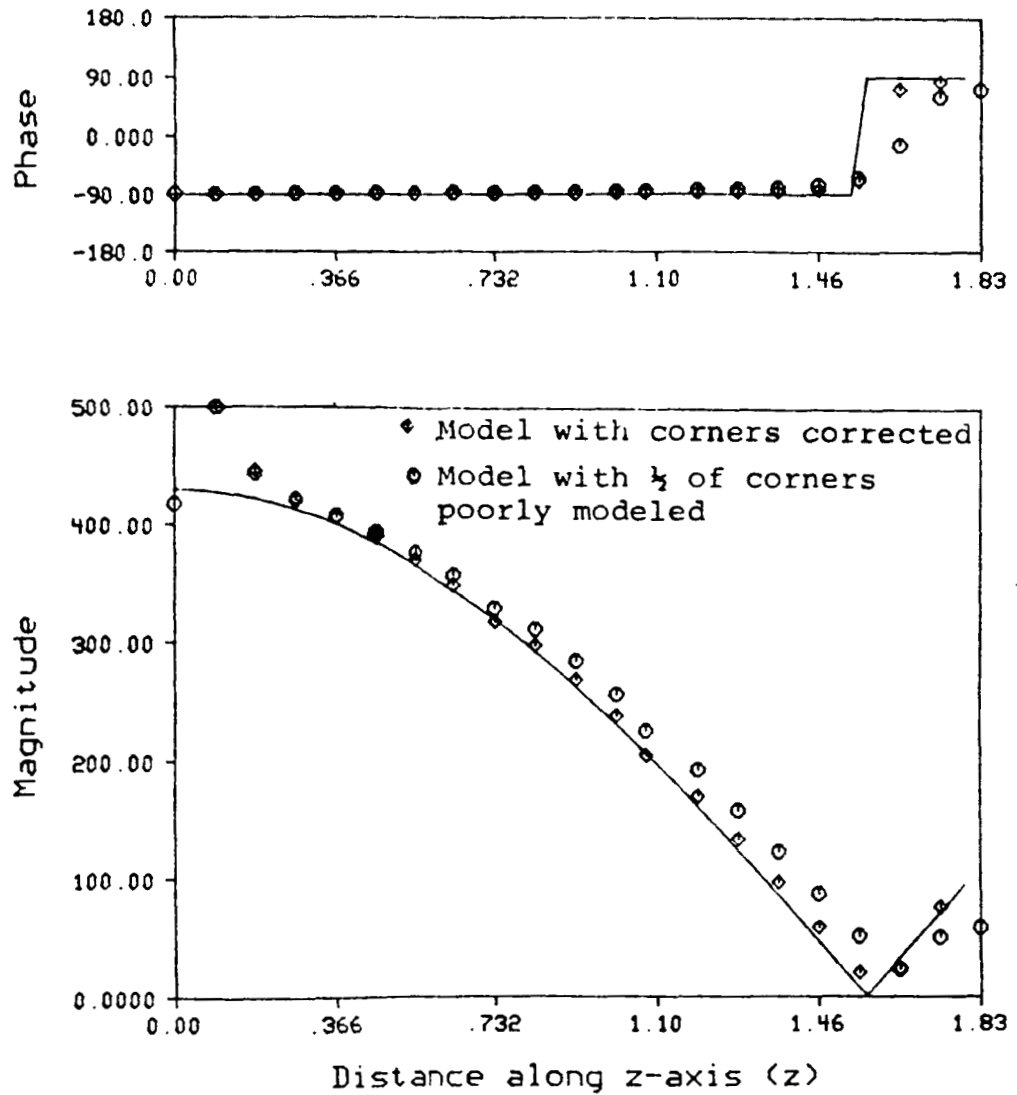
Interior pressure distribution in box with one

end pulsing with a volume velocity of 1.

Figure 1-2.

package, for demonstration at the Herrick Lab. The STSF system is a noise source identification procedure which uses both holographic principles and the Rayleigh integral equation. Of most significance to the current NASA research is the hardware implementation of STSF which is similar to that required for the DBEM procedure. From this demonstration, the experimental/analytical DBEM noise source identification method appears to be feasible.

IDENTIFICATION OF STRUCTURE-BORNE NOISE PATHS USING STRUCTURAL INTENSITY (J. Mickol)

During the reporting period J. Mickol finished his research investigations and successfully passed the defense of his Master's of Science thesis. Thus, a complete report of his investigations in the form of his thesis will be sent to NASA as soon as the thesis is duplicated. For purposes of this report the most significant findings of his research will be summarized here.

Structural intensity measurement is potentially a very powerful technique for the identification of structure-borne noise sources, sinks and paths. However, as previous investigators have pointed out, the two accelerometer implementation of structural intensity is quite limited in its application. In particular, it has been demonstrated that the method may only be used for measurement of flexural wave energy in the farfield of the plate in vibration fields where a significant part of the motion is due to active energy transport rather than standing

waves. The method is also subject to high and low frequency limits due to the sensitivity of the probe and the finite difference approximation. The technique also suffers in accuracy when significant phase and gain mismatch exist between the two measurement channels.

This investigation has been concerned primarily with the applicability of the two accelerometer structural intensity implementation in thin plate structures typical of aircraft. A previously unreported limitation of the intensity measurement is discussed in this investigation. It was discovered that the inertia of the probe significantly affects the power input to a thin plate. When the inertia of the probe is compensated the intensity apparently is accurately measured. The accuracy of intensity measurement is verified by integrating intensity over a surface and comparing the power to measured input power. Under well controlled conditions the integrated power and input power are very well matched.

The sensitivity of the intensity measurement to probe inertia was also demonstrated theoretically using a beam solution. It was found that for a typical beam with typical probe inertias, the injected power to a beam is very sensitive to probe location and inertia. It was also shown that such sensitivity also changes with damping (i.e. the active component of energy flow).

To complement the measurement of intensity for structural modeling and for complex structures, the structural intensity

calculation was formulated for the finite element method. A popular finite element code, ANSYS, was used for this study. The implementation required some postprocessing. However, the finite element formulation was successfully verified for both one-dimensional and two-dimensional geometries. The method can be used to identify power flow in built-up structures. In addition, the resulting intensity computations can be directly compared with measurements to verify models and identify system behavior.

DESIGN OPTIMIZATION OF ACTIVE NOISE CONTROLLERS (Chris Mollo)

Because of the amount of computations involved in a controller study using OPCON and the quantity of controller studies that were to be performed, it was decided to implement the program on a much larger computer. The program is currently being run on a CYBER 205.

A different formulation in the study of optimal active noise controllers was developed in conjunction with a fellow graduate student. The active noise control system to be studied is described in Fig. 3-1. The system is comprised of a boundary, canceling sources (secondary sources), uncontrollable acoustical point sources (primary sources), measurement locations, and performance state locations. The purpose of this approach is to find the optimal solution for the transfer function between the measurement(s) and the secondary source(s), C(w), using a performance equation which may or may not use measurement location data. Once C(w) was found it was inversed Fourier transformed to
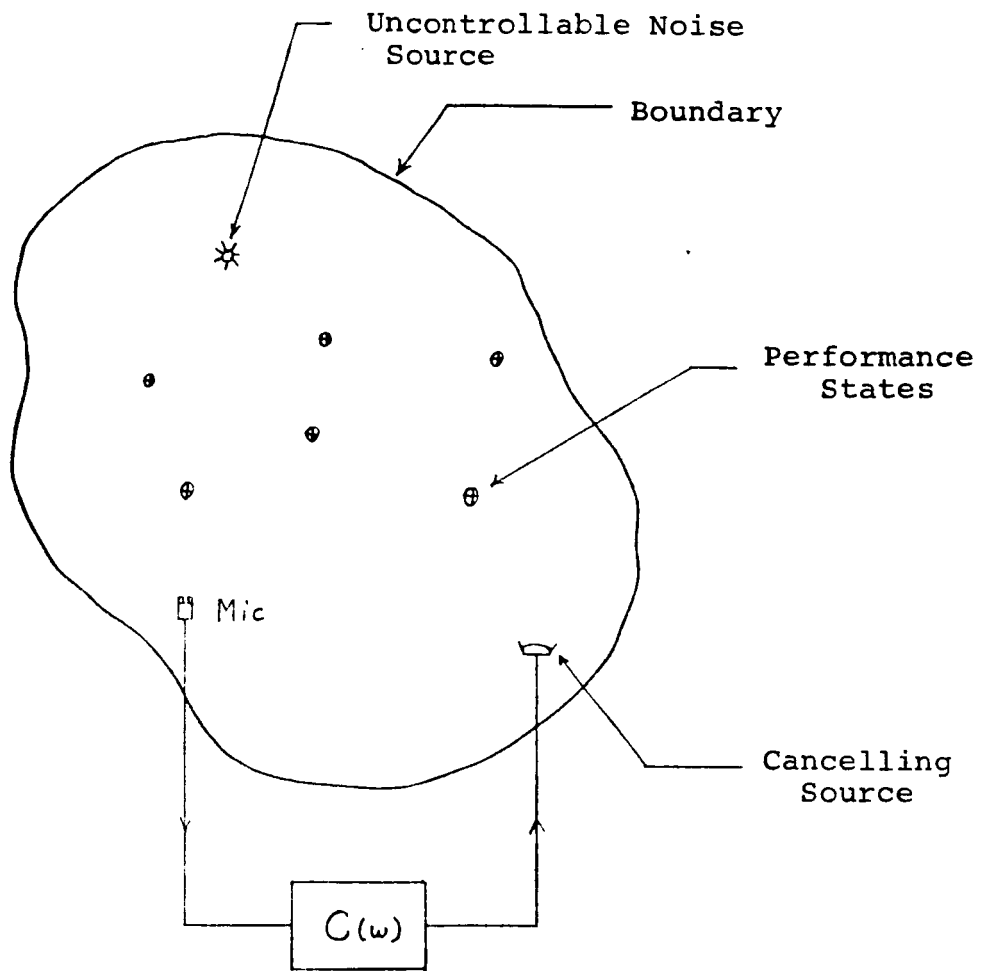
Figure 3-1. System description

obtain its impulse response function. A program using the IBEM was developed which provides C(w) in discrete form. This formulation appears to yield information about the observability and causality of the control system. Some preliminary results have been obtained which will be discussed in future reports.

After running several more preliminary controller studies with OPCON, three controller design topics were investigated. First, the best placement of the secondary source when the noise producing source is compact was investigated. A primary source of strength 1 m^3/sec was placed at the center of a rigid walled sphere. A secondary source was then placed at distances of 0.01, 0.1, 0.2, 0.3 and 0.5 away from the primary source. See Figs. 3-2 and 3-3 for results for distances of 0.1, 0.2, 0.3. As the secondary source is moved closer, the performance increases and the solution approaches that of a dipole. For a distance of 0.01 the solution is almost identical to a dipole and the attenuation is greatest (see Figs. 3-4 and 3-5). Thus, for compact noise sources it is best to place your canceling source as close as possible although significant attenuation is usually possible at cavity resonances even when the secondary source is removed from the primary source.

Second, the placement of the secondary source for best performance when the noise source is distributed was investigated. Four neighboring elements were given an oscillatory velocity motion while the remaining 44 elements were given rigid walled boundary conditions. A secondary source was placed on a radial
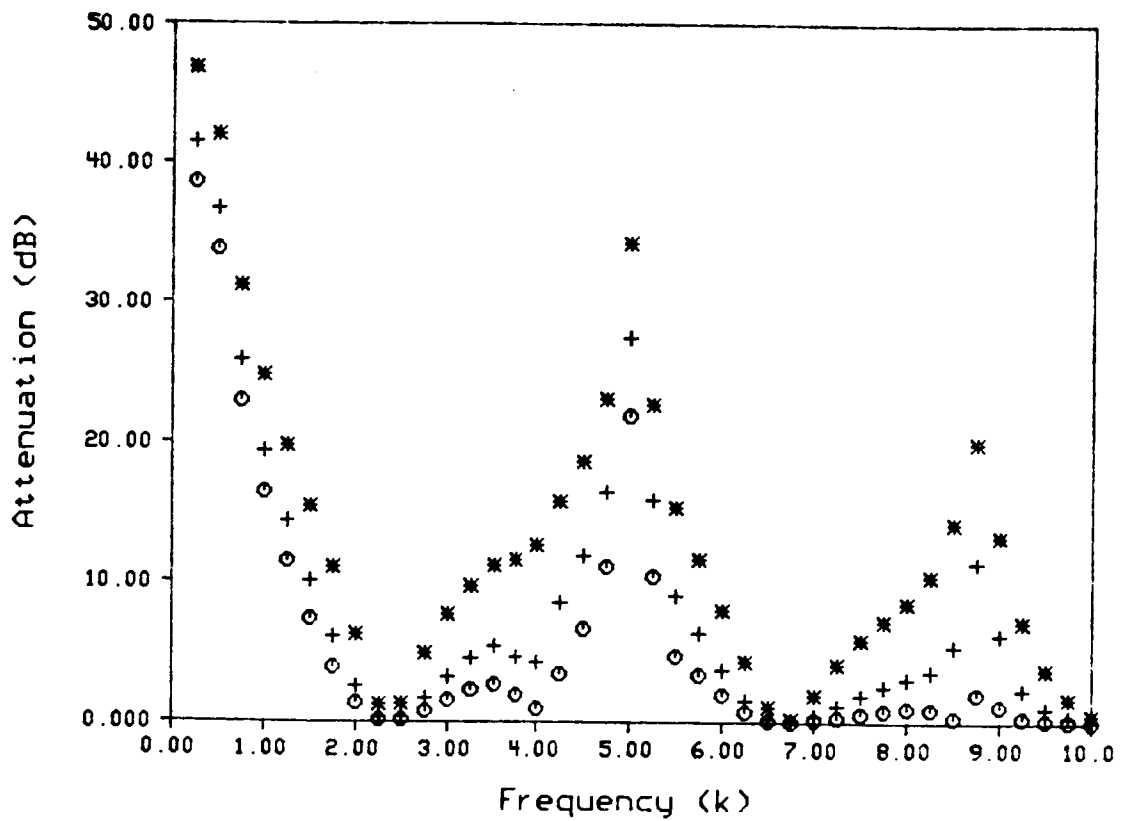
Figure 3-2. The attenuation of a secondary source as a function of distance from a compact primary source inside a rigid cavity. *d=0.1, +d=0.2, ⊙ d=0.3.
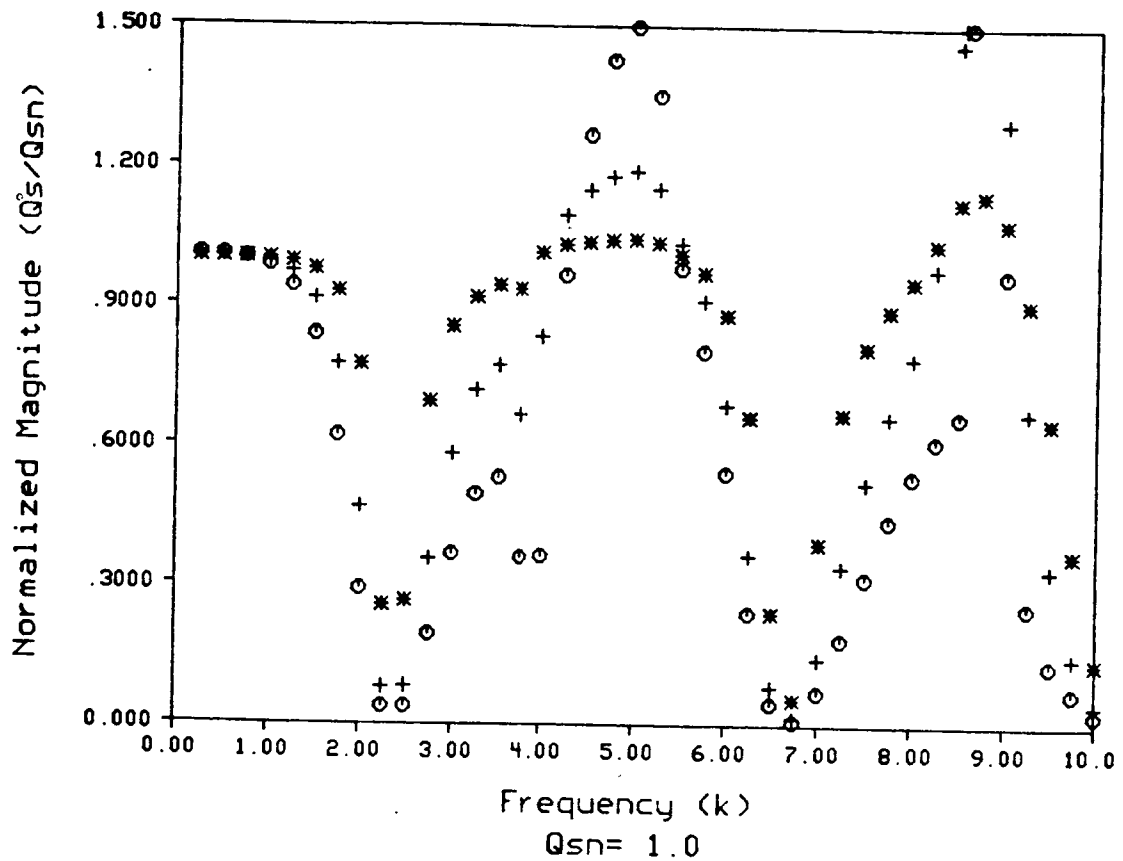
Figure 3-3.   Secondary source strength as a function
              of distance from a compact primary
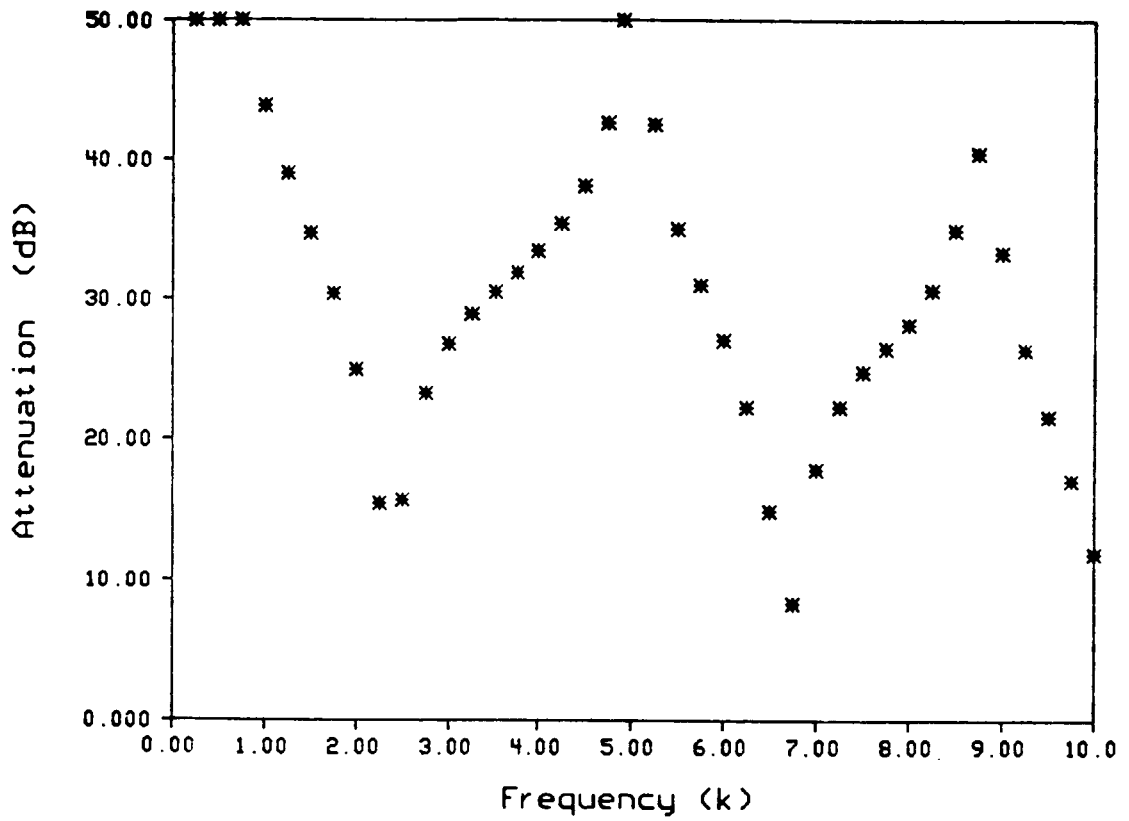   source in a rigid cavity.   *d=0.1,
              +d=0.2, o d=0.3.

Figure 3-4. Attenuation of a secondary source tightly coupled (d=0.01) to a compact primary source inside a rigid cavity.
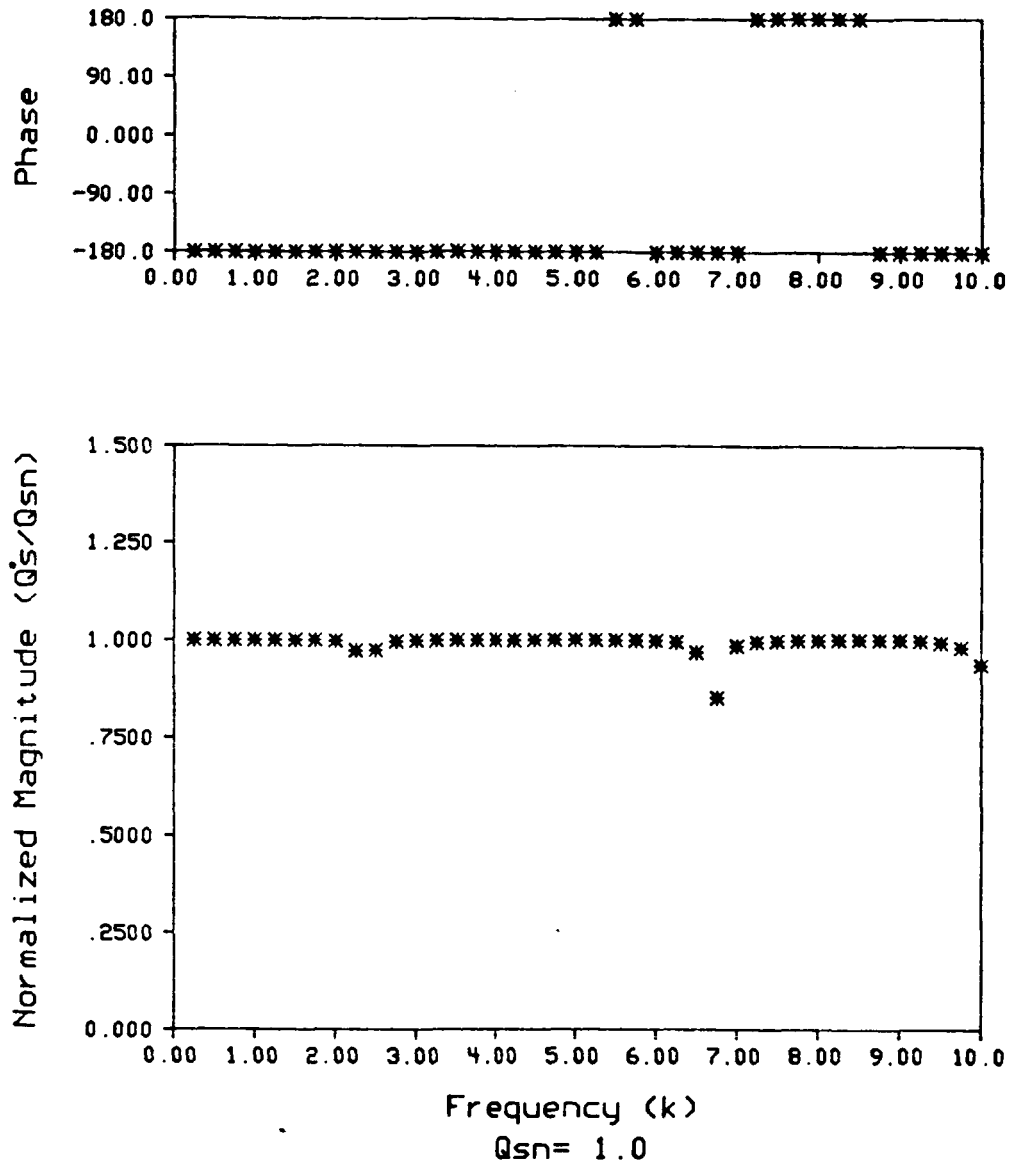
Figure 3-5.   Source strength of the secondary source
               tightly coupled (d=0.01) to a compact
               primary source inside a rigid cavity.

line at distances of 0.1, 0.2 and 0.3 away from the centroid of the combined four elements. In this case there is no significant change in the attenuation achieved as the secondary source position changed (see Fig. 3-6). Thus, for distributed sources in cavities, secondary source placement near a primary source is not particularly effective.

Third, the placement of the secondary source for local control was investigated. By using one secondary source, the pressure at any one observation point can be completely canceled. Thus, we wish to examine how the required secondary source strength changes as the source is moved close to and away from the single observation point. One observation point was chosen inside of a pulsating 48-element polygon. The secondary source was placed at distances of 0.1, 0.2 and 0.3 away from the observation point. The results are summarized in Fig. 3-7. No one secondary source position provides lower source strength at all frequencies. However, if the secondary source strength is averaged over all frequencies for each position, the average source strength increases as the secondary source is moved away from the observation point:

$$\overline{(Q_s^o/Q_{sn})}_{0.1} = 0.221$$

$$\overline{(Q_s^o/Q_{sn})}_{0.2} = 0.350$$

$$\overline{(Q_s^o/Q_{sn})}_{0.3} = 0.471$$

The IBEM was verified for the rectangular acoustic domain. In order to verify the IBEM, one end of the rectangular cavity
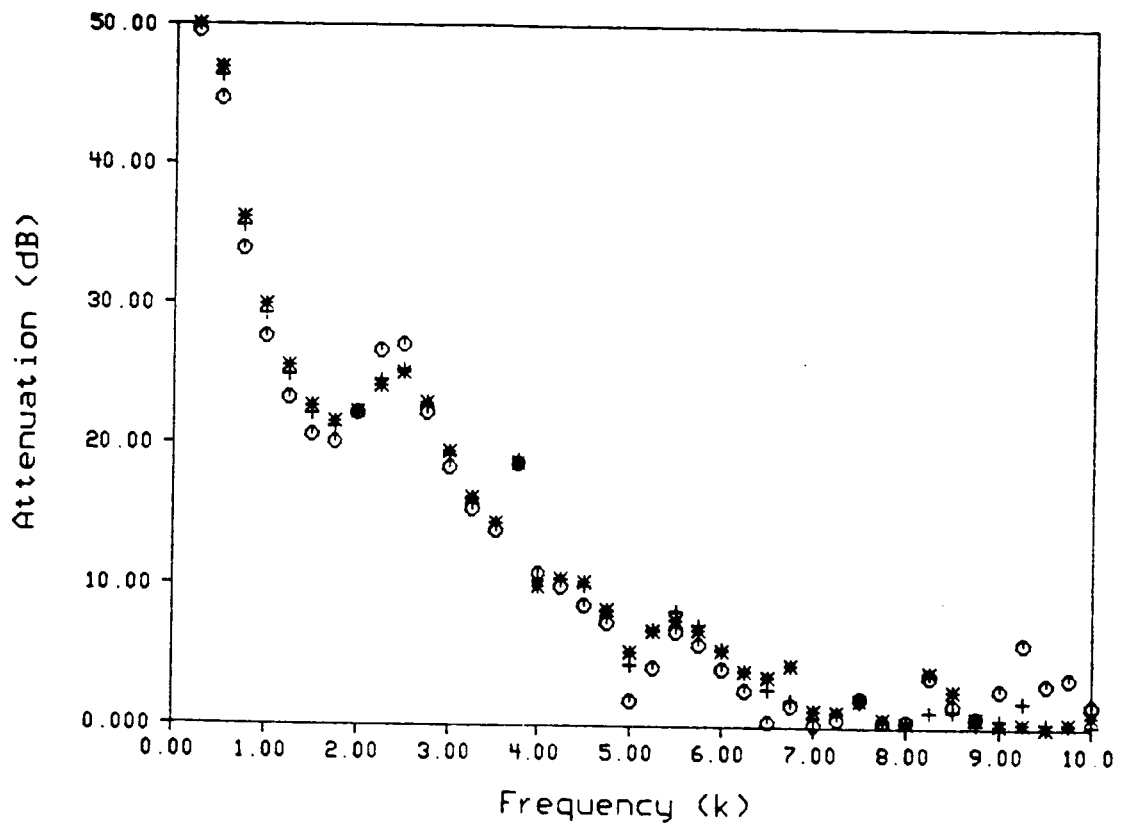
Figure 3-6. Attenuation of a distributed source by a
single secondary source as a function of
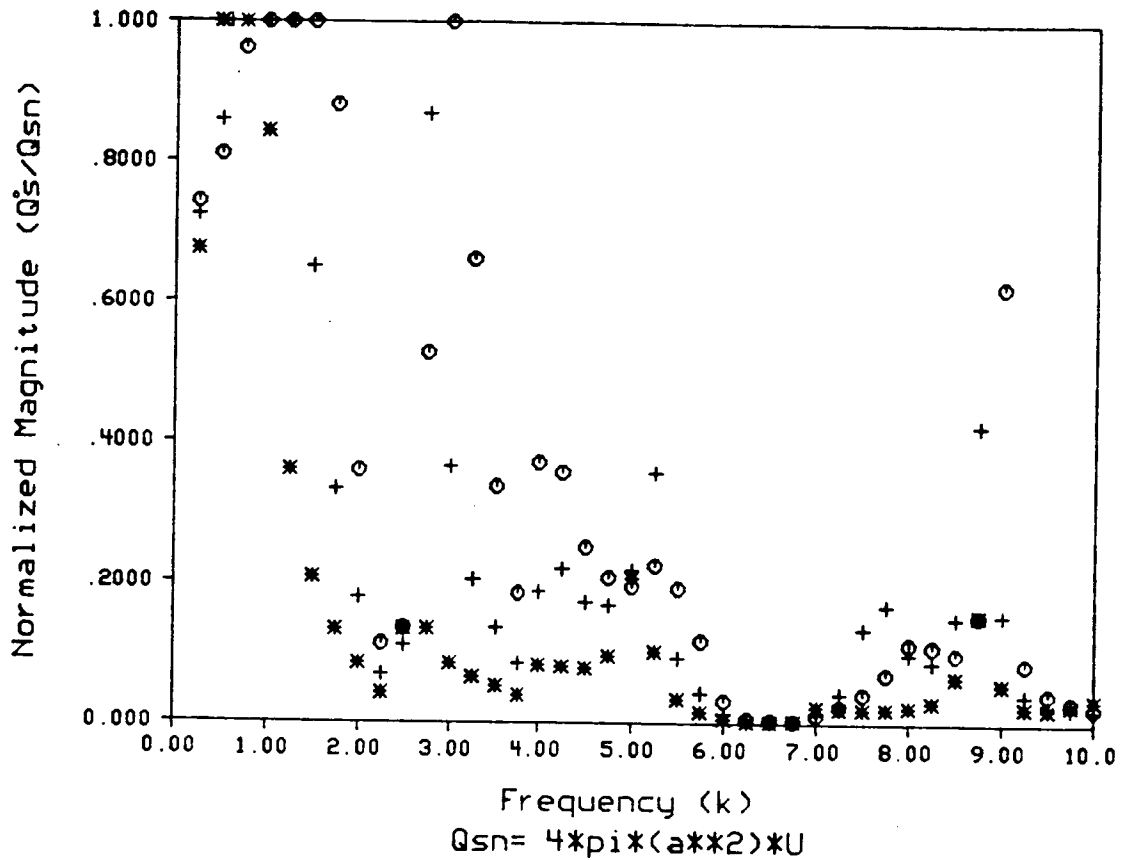separation in a rigid cavity. *d=0.1,
+d-0.2, o d=0.3.

Figure 3-7. Source strength required to achieve local cancellation in a pulsating polyhedron as a function of distance from the control point. *d=0.1, +d=0.2, o d=0.3.

was given a uniform velocity boundary condition. The other five sides were given rigid wall boundary conditions. The frequency was kept low to ensure one-dimensional acoustic behavior. Fig. 3-8 illustrates the results for several situations. Fig. 3-8(a) shows the results using the 80 element model for a point near the center of the cavity. Fig. 3-8(b) shows the results using the 80 element model for a point located near a corner of the cavity. Figs. 3-8(c) and 3-8(d) show results using the 156 element model for points located near the center of the cavity and near a corner of the cavity, respectively. The results are very good throughout much of the cavity but get poorer near corners and edges due to integration error. When the techniques discussed by Gardner are implemented the results in 8b and 8d should improve.

The ability to calculate the source power output for secondary sources and primary sources was added to OPCON. The source power output derivation was verified by implementing it into an IBEM program. A simple source was placed at the center of the 48 element sphere model. The boundary was given either pressure or impedance boundary conditions which would simulate free field radiation. The source power calculated by the IBEM was within 1% of the analytical solutions for both types of boundary conditions.
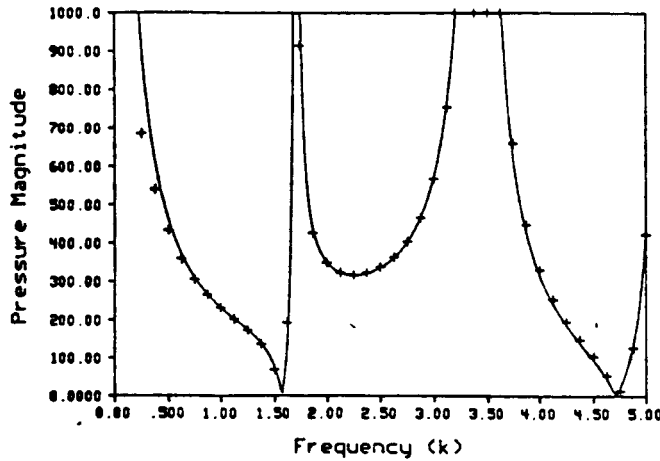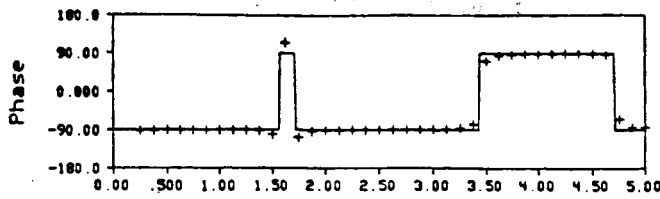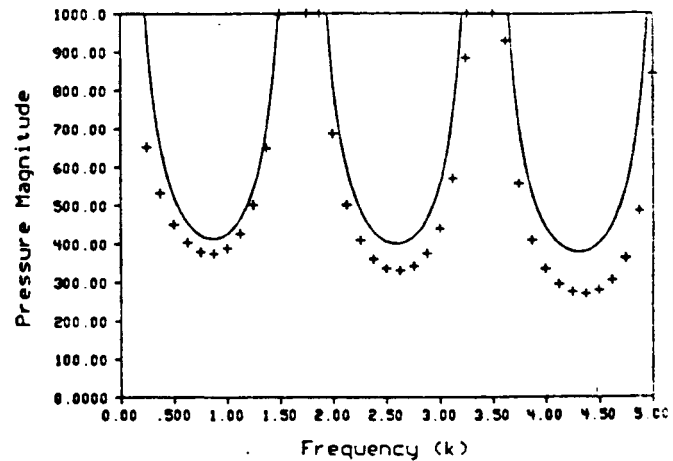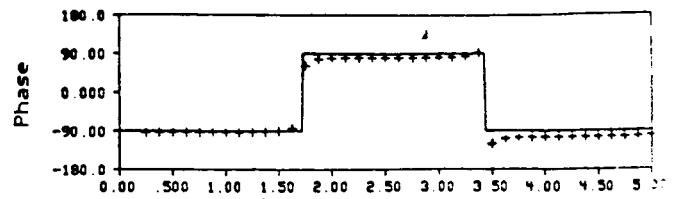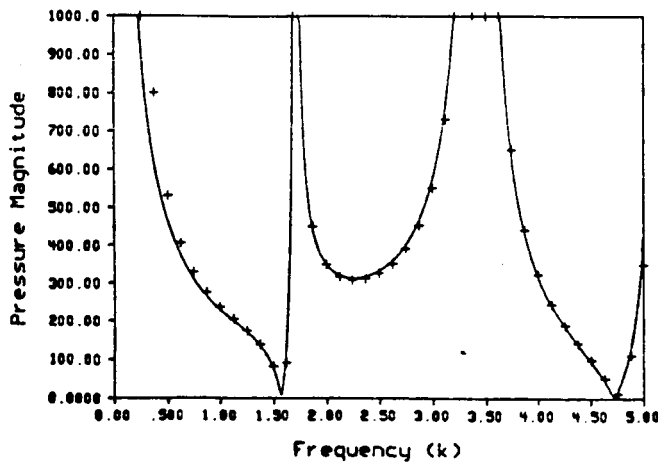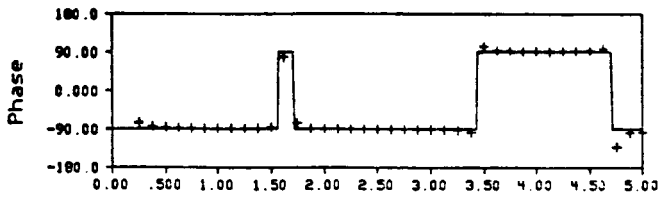
Figure 3-8.   Verification of the rectangular cavity models;
a) center point, so element model, b) corner point,
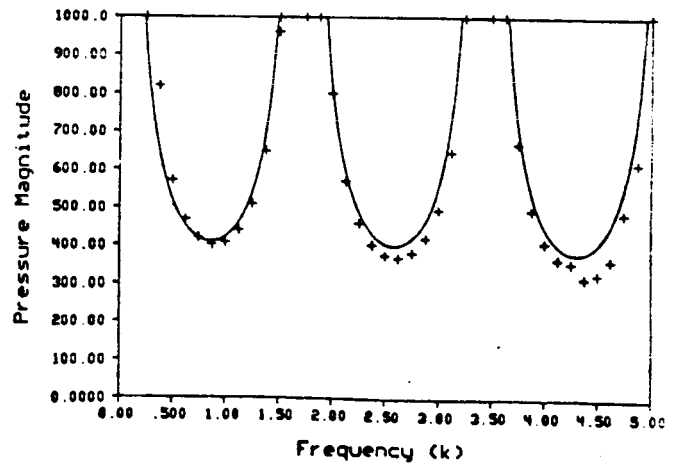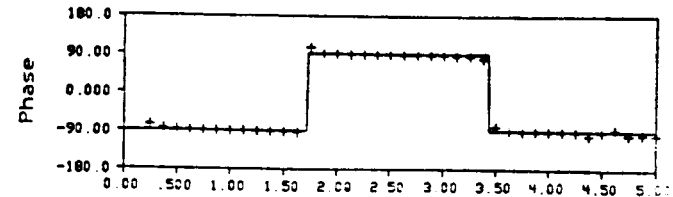80 element model, c) center point, 156 element
model, d) corner point, 156 element model.

DYNAMIC PROPERTIES OF ACOUSTICAL FOAMS (Christina Bruer)

During the reporting period work has continued on the measurement of the dynamic elastic properties of relatively stiff, partially reticulated foams. Knowledge of these properties is necessary to allow accurate modeling of three-dimensional sound transmission through foam as used in fuselage lining treatments. The measurement procedure used to-date is similar to that prescribed in ASTM standard E756-83 (standard method for measuring vibration-damping properties of materials) and is based on theoretical work by Kerwin, Ross and Ungar, and by Oberst. Values of both the Young's modulus and the shear modulus (and their associated loss factors) may be deduced from measurements of the acceleration/force transfer function of a free-free sandwich beam.

In the case of the Young's modulus, a layer of foam 1/4 inch thick is applied to a 1/8 inch thick aluminum bar. According to the ASTM technique, measurements of the beam resonant frequencies and the one-half power bandwidth of the resonances will yield the Young's modulus and the loss factor as a function of frequency. However, accurate estimation of the resonant frequencies from frequency response plots is difficult when the beam is heavily damped as in the present case. As a result, a new procedure has been developed in which the resonant frequencies and the damping at each resonance are found by fitting a modal model to the measured beam transfer function. The fit is performed using a non-linear least squares procedure (the Lever-Marquandt algorithm).

The technique has proven satisfactorily robust. First estimates of the Young's modulus and loss factor found by using it are consistent with those deduced by Bolton and Green from measurements of sound transmission through foam layers (see references 6 and 7).

More recently attention has been focused on the somewhat more difficult task of measuring the shear modulus of foam. Again, the measurement involves observation of the resonant response of a free-free beam, but in this case the beam consists of a foam core sandwiched between two aluminum bars. The ASTM technique (which has been discovered to be in error as published) is not appropriate in this case since it assumes that the core's Young's modulus is insignificant in this configuration. Measurements of the relative acceleration of the two aluminum bars have demonstrated that this is not the case. As a result, theories more complete (i.e., accounting for both shear and Young's moduli simultaneously) than the one on which the ASTM standard is based are being investigated. In particular the feasibility of using theories by either Mead or Miles is being tested. In addition, a complete propagating wave model will be developed for this beam configuration against which the other theories may be tested. Once an appropriate theory is selected it will be used in conjunction with a non-linear least squares algorithm to deduce the foam's shear modulus. This work will result in a significant extension of current techniques for the measurement of material damping properties and will also allow the prediction of the

damping behavior of foam layers when applied to panels (as in fuselage lining configurations).

In addition, a vacuum chamber large enough to accommodate the free-free beam test apparatus has been constructed to allow the dynamic moduli to be measured in vacuo. In this way the damping effect of air motion within the foam's pores may be minimized and the separate contributions of the foam's solid part and the contained air to the total damping can be established.

Finally, some time was devoted to development of periodic deterministic signals (so-called Schroeder-phase signals) for use in the beam tests. These signals allow time domain averaging to be performed to improve experimental signal to noise levels. In addition tests performed in this way do not suffer from bias and leakage errors which distort transfer functions measured using random input signals. Hardware and software has been developed to allow frequency response testing using these new signals.

MEASUREMENT OF THE SOUND FIELD IN THE HP137 JETSTREAM III (Chris
Wohlever)

During the latter part of the reporting period, two tests
were run on the operational HP137 Jetstream III. The first test
was primarily a checkout run but some useful data were collected.
For the first test, 15 microphones were attached to seat loca-
tions throughout the passenger cabin and multiplexed back to an
FFT and microcomputer storage device. A full set of data was
collected with one engine running followed by two sets of meas-
urements with both engines running at various engine power set-
tings. When the data is reduced it will be used to understand
the source field and to identify differences in the sound field
under the various conditions. In addition, the data will be used
to evaluate the repeatability of the tests.

For the second test, a reference microphone and a reference
accelerometer mounted to the trim were added to the test. The
reference signals were connected directly to one channel of the
FFT while the 15 multiplexed signals were connected to the second
channel. All the data necessary to compute coherence functions
and transfer functions were stored. Three power settings with
both engines operating were used. From the data we hope to
define the repeatability of our tests and to further characterize
the sound field in the cabin (i.e. standing wave or traveling
wave behavior) in anticipation of tests to be run in the spring
to identify primary mechanisms of noise in passenger cabins. In
addition, the second set of test data can be used to define the

requirements of our active noise controllers. From the data we should be able to determine how well the sound throughout the cabin is correlated and thus, how complicated the active control detector system must be. In addition, the reference accelerometer data should indicate whether a vibration sensor is a reliable input transducer.

Programs to reduce the data are currently being developed and the reduced data should be available early in 1987.

RELATED WORK OF POSSIBLE INTEREST TO NASA

There is significant interaction between NASA sponsored research and other investigations done at Purdue.

The NSF funded work on active noise control is continuing. A demonstration of acoustic modal control in a cavity using an analog controller is complete. Currently, a digital modal controller is in development. A second study is investigating the casualty and observability issues which Chris Mollo's IBEM programs allow us to simulate. We anticipate this work will allow us to identify sub-optimal controllers for control of transient and random noise sources.

Significant work has been reported in past progress reports on prediction of sound transmission through foam-lined double panel constructions. One of the investigations is complete with the successful defense of Ed Green's Master's of Science thesis. Copies of this thesis will be sent to NASA in the near future.

Professor Bolton has been in contact recently with one of our former students, Steve Marshall at Boeing Aerospace, who with Keith Wilson is conducting a series of tests to evaluate such treatments for the Boeing 7J7 program. Professor Bolton plans to extend Ed Green's investigations with a new Ph.D. research assistant who will be supported by internal Purdue fellowship monies.

TRAVEL

Funds from the grant were used to fund one domestic trip during the grant period. The trip was taken by the principal investigator to NASA Langley Research Center. Activities included presentation of the current progress of research and discussion of future directions of the grant.

PUBLICATIONS

Complete bibliographic citations of articles published during the grant period is included at the end of this report. Copies of various papers are being sent to NASA under separate cover.

REFERENCES

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3. R.J. Bernhard and C.G. Mollo, "Prediction of Optimal Active Noise Controllers Using Boundary Element Methods", Paper H Presented at the 111th Meeting of the Acoustical Society of America.

4. J. Mickol, "An Investigation of Energy Transmission Due to Flexural Wave Propagation in Lightweight Built-up Structures", MS Thesis, Purdue University, Dec. 1986.

5. M.S. Atwal, K.E. Heitman, and M.J. Crockor, "Prediction of Light Aircraft Interior Sound Pressure Level From the Measured Sound Power Flowing into the Cabin," Proceedings of Internoise 86, July, 1986, pp. 1045-1048.

6. J.S. Bolton and E.R. Green, "Sound Transmission Through Double Panel Constructions Lined with Elastic Porous Materials," AIAA Paper No. AIAA-86-1907, July, 1986.

7. E.R. Green, "Normal Incidence Sound Transmission Through Panel Constructions Containing Relatively Stiff, Partially Reticulated, Plastic Foam", M.S. Thesis, Purdue University, Dec. 1986. M.S. Thesis, Purdue University, Dec. 1986.

8. J.S. Bolton and E.R. Green, "Acoustic Energy Propagation in Noise Control Foams Approximate Formulae for Surface Normal Impedance," Paper E4, presented at 112th meeting of the Acoustical Society of America.